# DEVELOPMENT OF A UNIFIED DESCRIPTION OF SHIP-GENERATED WAVES
## (and some other recent work)


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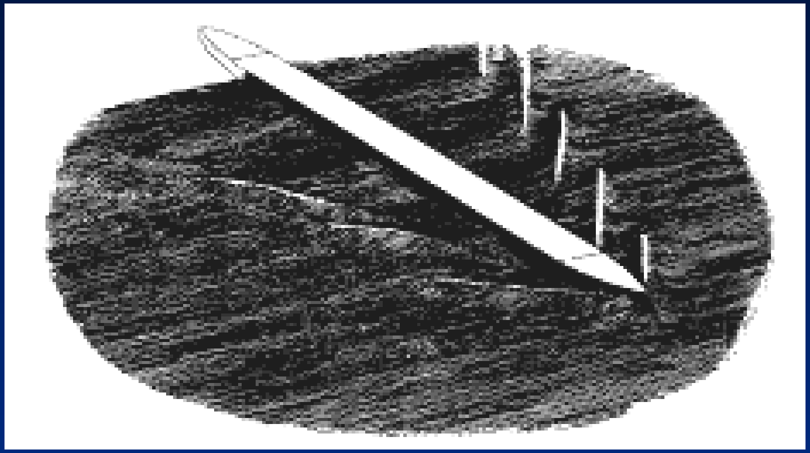
    *US Naval Academy*

## Outline of Presentation

- **Ship Generated Wave Height**
- **Ship Squat in Shallow Water**
- **Mooring Loads from Passing Vessels**

# Objectives
# Ship-Generated Wave Heights

- **Develop empirical equation to predict maximum ship-generated wave heights**
  - For large displacement hulls, no fast ferries or planing craft

- **Improve upon existing predictive equations:**
  - Gates and Herbich (1975)
  - Sorensen and Weggel (1984) & Weggel and Sorensen (1986)
  - PIANC (1987)

- **Use existing data published in the literature**
  - Seek to "unify" data from various sources

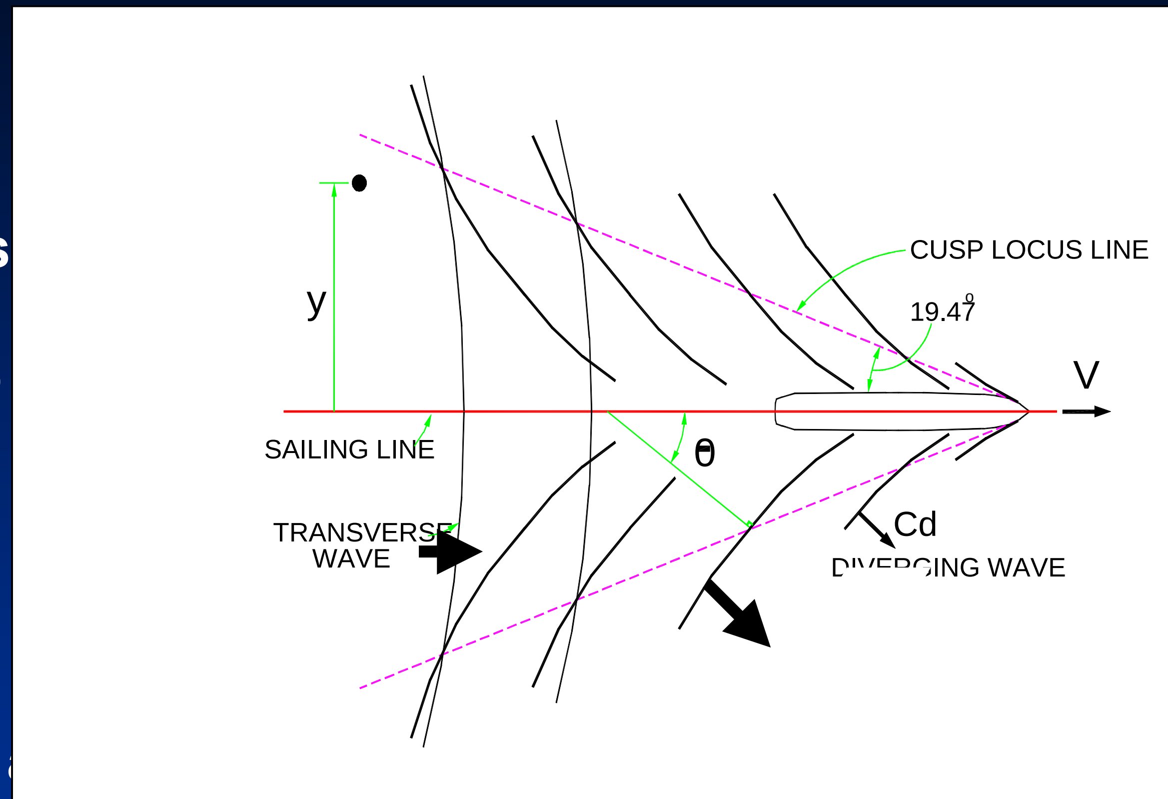
- **Run new lab tests to supplement existing data**
  - Tests conducted in Naval Academy towing tanks

# Background

- **Some Ship-Generated Wave Height Data in the Literature:**
  - **“Wake Wash” of Fast Ferries**
    - Kofoed-Hansen and Kirkegaard (1996), Kofoed-Hansen and Mikkelsen (1997), Danish maritime Agency (1997), Kirkegaard et al (1998), Kofoed-Hansen et al (1999), Gadd (1999), Stumbo et al (1998, 1999), Whittaker et al (1999, 2000), Leer-Anderson et al. (2000), UK Maritime and Coastguard Agency (2001)
  - **Waves Generated by Recreational Boats**
    - Zabawa and Ostrom (1980), Bhowmik (1975), Bhowmik et al (1982, 1991, 1992), Bhowmik and Soong (1992), Sorensen (1997)
  - **Deep-Draft Commercial Ships**
    - Johnson (1958, 1968), Biddie (1968), Brebner et al. (1966), Carruthers (1966), Das (1969), Hay (1967, 1968), Helwig (1966), Gates and Herbich (1977), Sorensen (1966, 1966, 1967, 1968, 1973, 1986, 1997), Sorensen and Weggel (1984), (Kurata and Oda (1984), Weggel and Sorensen (1986), PIANC (1987)

# Definitions

- **Two wave systems:**
  - **Diverging Waves**
    - **Move at angle θ relative to ship**
  - **Transverse Waves**
    - **Move in same direction as ship**
- **Maximum wave heights**
  - **Form along “Cusp where transverse diverging waves meet**
  - **Vary with distance from sailing line, y**



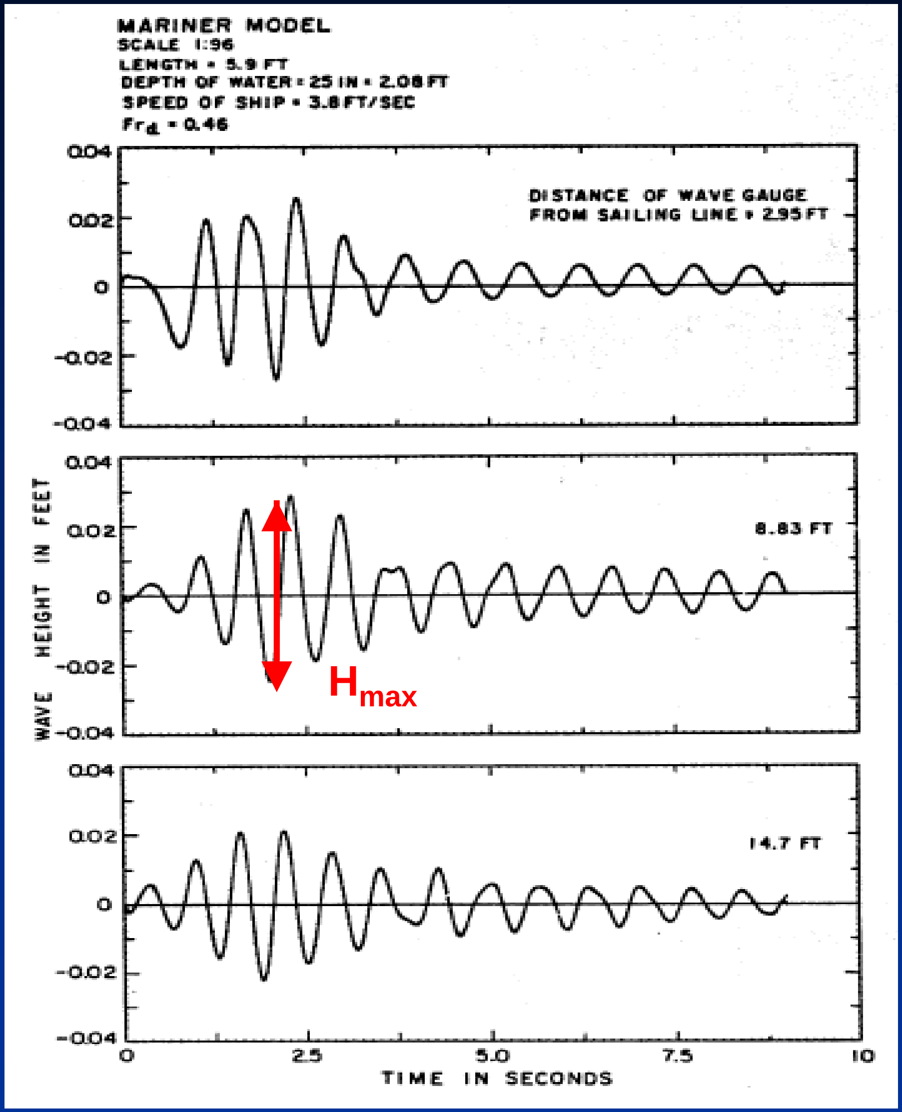

**SAMPLE SHIP-GENERATED WAVE PATTERN FOR DEEP WATER**

**(after Sorensen, 1997)**

# Sample Wave Records
## from Literature

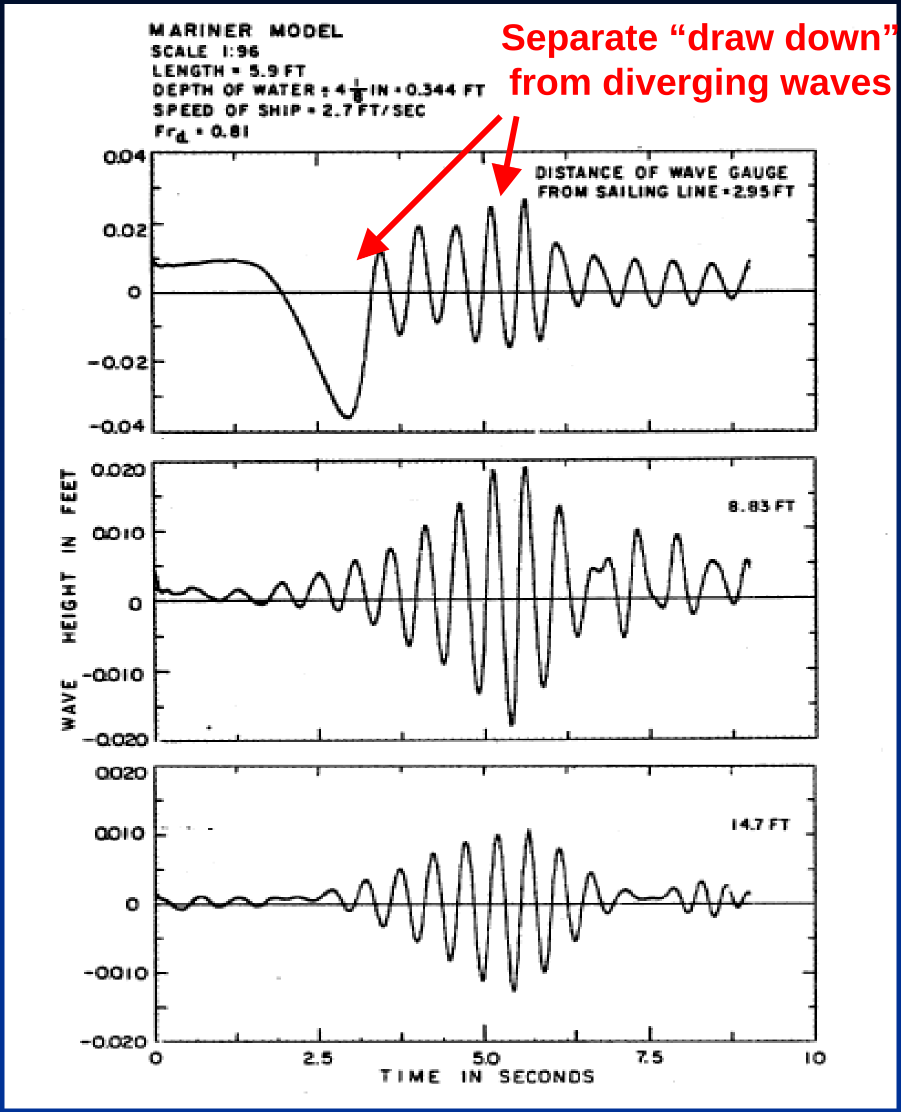
**Deep Water**

from Das (1969)



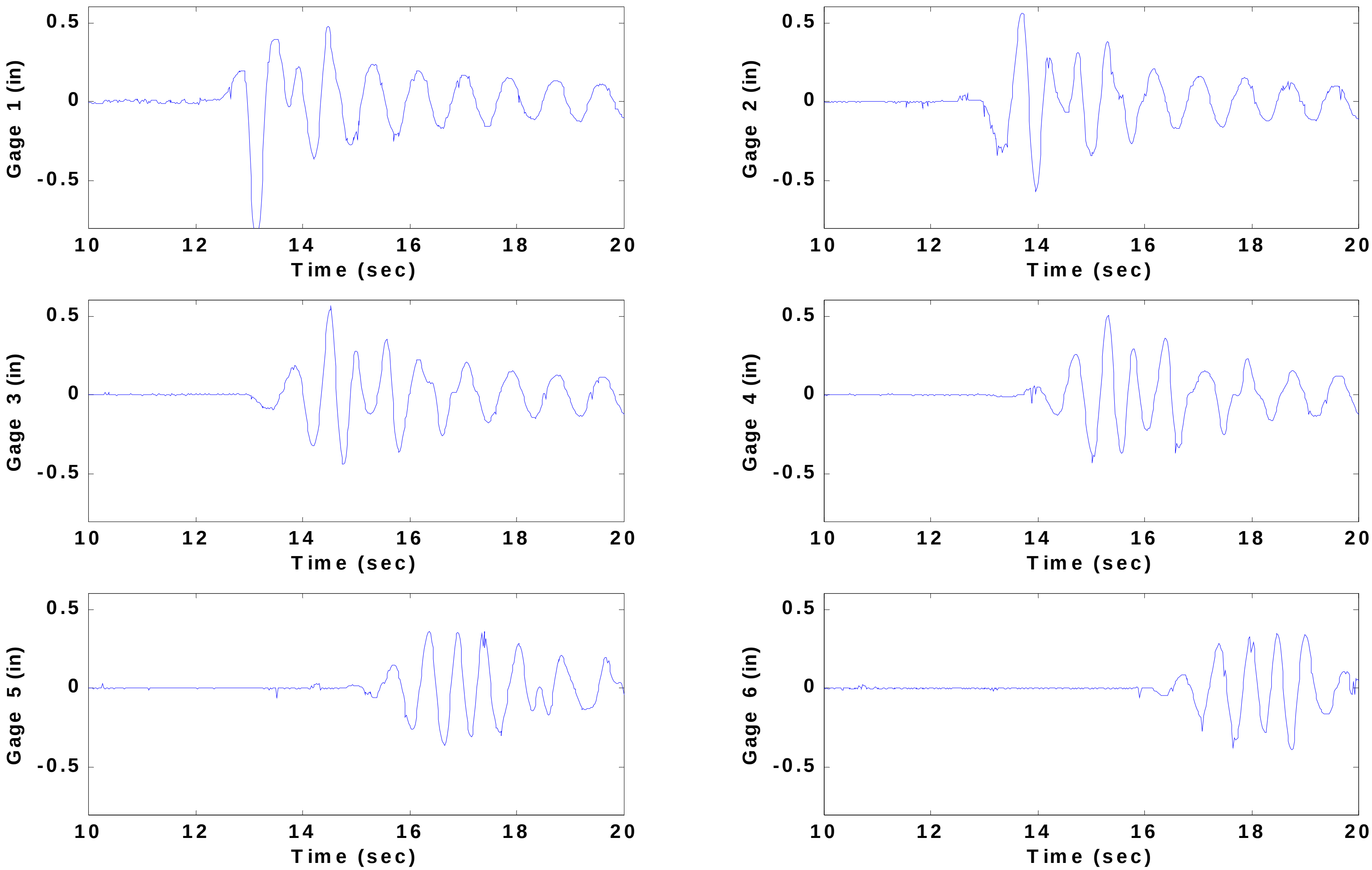

**Shallow Water**

from Das (1969)



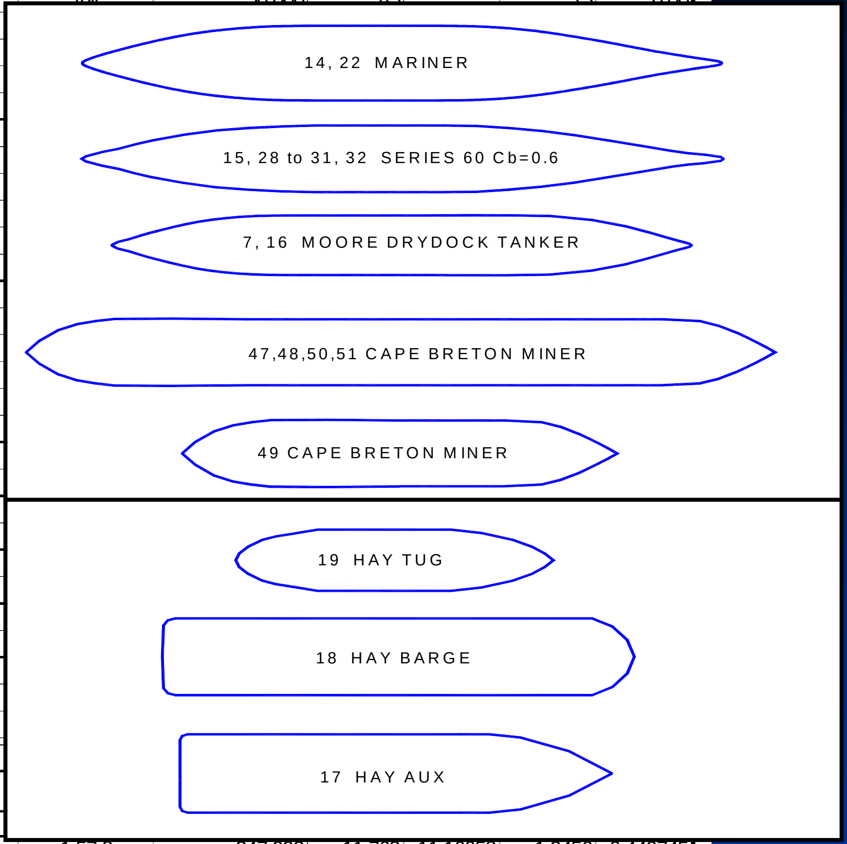
# Examples from Naval Academy Tests

## Waves measured at 6 distances y off sailing line



# Ship Wave Database

| Ship Number | Investigator | Scale for Rx=10 m | Vessel | Scale | Displacement (lbs) | Length (feet) | Lwl (feet) | Beam (feet) | Draft (feet) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Sorensen (1973) | 8.73 | **Cabin Cruiser** | full | 6,000 | 23 | | 8.3 | 1.70 |
| 2 | | 8.58 | **Coast Guard Cutter (40-FOOT)** | full | 19,730 | 40 | 37 | 10.7 | 1.91 |
| 3 | | 3.71 | **Tugboat** | full | 58,000 | 45 | | 13 | 6.00 |
| 4 | | 5.29 | **Air-Sea Rescue Vessel** | | | | | | |
| 5 | | 1.87 | **Fireboat** | | | | | | |
| 6 | | 1.18 | **Barge** | | | | | | |
| 7 | | 0.77 | **Moore Dry Dock Tanker** | | | | | | |
| 8 | Sorensen (1966) | 185.59 | **Model A** | | | | | | |
| 9 | | 139.12 | **Model B** | | | | | | |
| 10 | | 111.40 | **Model C** | | | | | | |
| 11 | | 92.80 | **Model D** | | | | | | |
| 12 | | 69.61 | **Model E** | | | | | | |
| 13 | | 77.83 | **Weinblum hull** | | | | | | |
| 14 | Hay (1967) | 76.11 | **Mariner Class Cargo Ship** | | | | | | |
| 15 | | 81.58 | **SERIES 60 Cb=0.6** | | | | | | |
| 16 | | 74.05 | **Moore Dry Dock Tanker** | | | | | | |
| 17 | | 58.20 | **Auxiliary Supply Vessel** | | | | | | |
| 18 | | 57.02 | **Barge** | | | | | | |
| 19 | | 47.88 | **Tug** | | | | | | |
| 20 | Bidde (1968) | 76.11 | **Mariner Class Cargo Ship (A)** | | | | | | |
| 21 | | | **Barge (E)** | | | | | | |
| 22 | Das (1969) | 76.11 | **Mariner Class Cargo Ship** | | | | | | |
| 23 | | | **Cruiser** | | | | | | |
| 24 | Zabawa & Ostroa (1980) | | **Uniflight Cruiser** | | | | | | |
| 25 | | | **Boston Whaler** | | | | | | |
| 26 | Kurata & Oda (1984) | 64.76 | **Ferryboat** | | | | | | |
| 27 | | | **Tugboat** | | | | | | |
| 28 | USNA (2000) | 78.58 | **SERIES 60 Cb=0.6 MID** | | | | | | |
| 29 | USNA (2000) | 75.40 | **SERIES 60 Cb=0.6HEAVY** | | | | | | |
| 30 | USNA (2000) | 83.10 | **SERIES 60 Cb=0.6 LIGHT** | | | | | | |
| 41 | Helwig (1966) | | **Empress of Canada (Ocean Liner)** | | | | | | |
| 42 | Helwig (1966) | | **M.S. Wearfield (Ocean Freighter)** | | | | | | |
| 47 | Carruthers (1966) | 73.54 | **Cape Breton Miner Bulk Carrier No Bulb** | | | | | | |
| 48 | Carruthers (1966) | 44.28 | **Cape Breton Miner Bulk Carrier No Bulb** | 1:57.8 | 347.992 | 11.763 | 11.16058 | 1.2456 | 0.449745 |
| 49 | Carruthers (1966) | 44.28 | **Cape Breton Miner Bulk Carrier No Bulb SHORT** | 1:57.8 | 191.718 | 7.092146 | 6.489276 | 1.2456 | 0.449745 |
| 50 | Helwig (1966) | 71.56 | **Cape Breton Miner Bulk Carrier Bulb** | 1:96 | 81 | 7.0833 | 6.72 | 0.75 | 0.286 |
| 51 | Helwig (1966) | 71.56 | **Cape Breton Miner Bulk Carrier No Bulb** | 1:96 | 81 | 7.0833 | 6.72 | 0.75 | 0.286 |

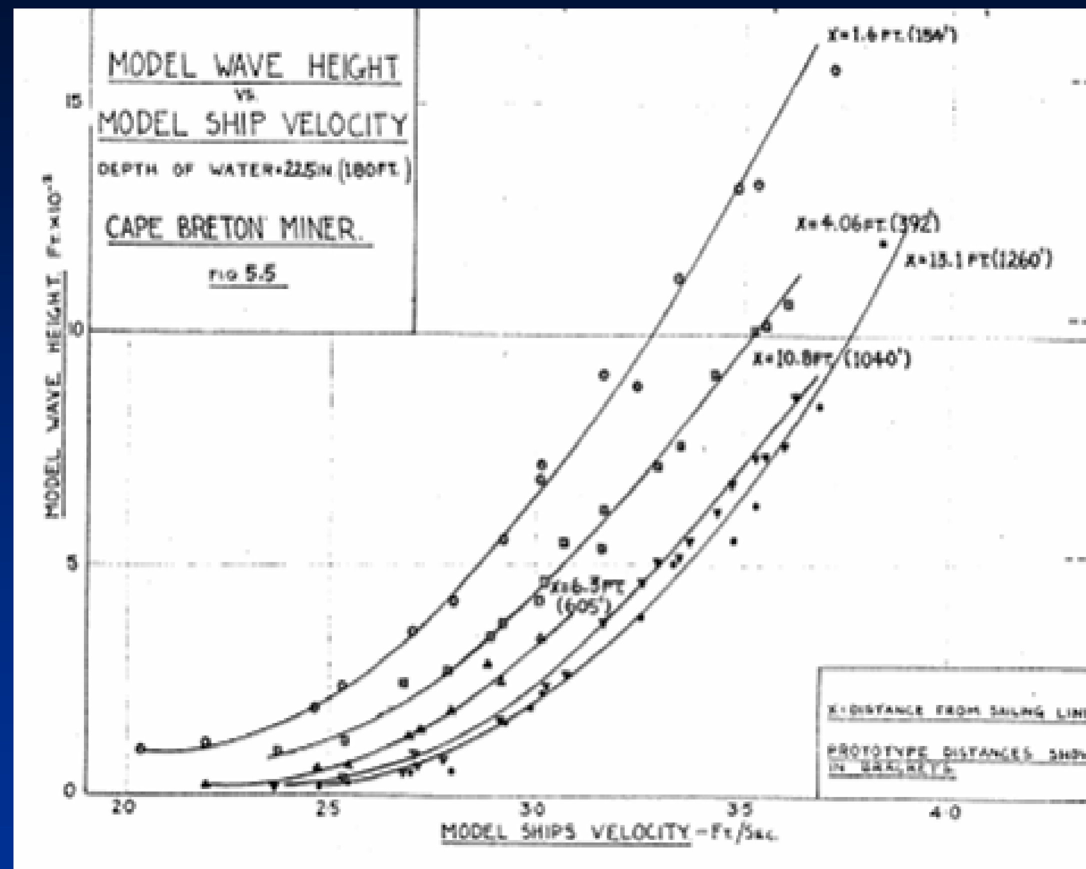



**Ship wave data used in present analysis:**

**2100 data points for 12 ships**

# Sample Wave Data
## from Literature

- **Wave heights given in:**
  - Tabular form
  - Graphical form
- **Wave Heights, H, vary with:**
  - Ship speed, V
  - Distance from sailing line, y
  - Water depth, d
  - Hull form




(FROM HELWIG, 1966)

# Analysis of Wave Heights

- **Wave height normalized by velocity head**

  $gH/V^2$

- **Distance from sailing line can be normalized in many ways (with length scales L, B, etc) …we use:**

  $y/L$

- **Data in shallow water organized by depth-to-draft ratio**

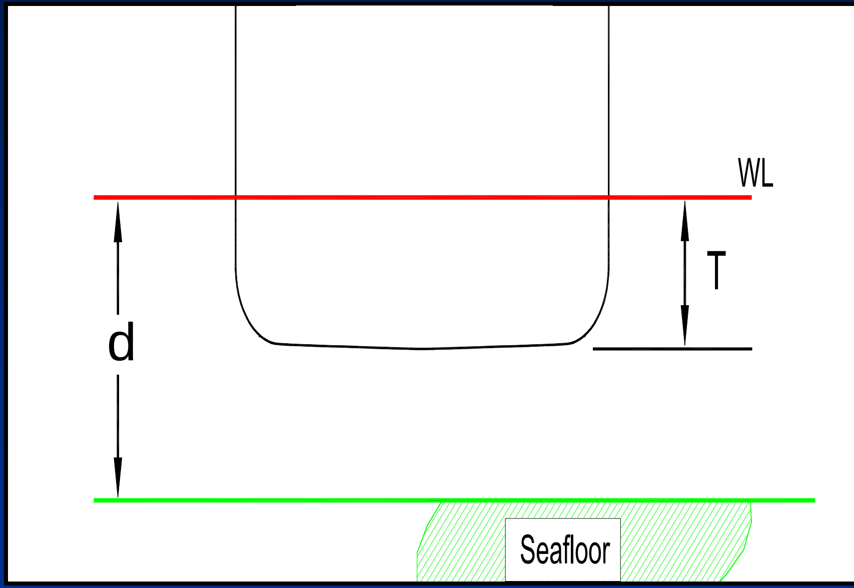
  $d/T$

- **Velocities normalized as Froude Number**

  $F_d = V/(gd)^{1/2}$ *or* $F_L = V/(gL)^{1/2}$

# Depth-to-Draft Ratio

- Wave heights strongly affected by depth-to-draft ratio, d/T
- No strong interaction with bottom if d/T > 3 to 5
- Typical commercial ships in navigation channels have d/T of 1.05 to 2
- Most wave data in literature for d/T from 1.4 to 3



# Which Froude Number to Use?

- **Length-Based Froude Number**
  - Used in deep water
  - Critical value $F_L = 0.4$
    - "Hull Speed" where transverse wavelength equals ship length
- **Depth-Based Froude Number**
  - Used in shallow water
  - Critical value of $F_d \sim 1.00$
    - ship speed exceeds shallow water wave speed

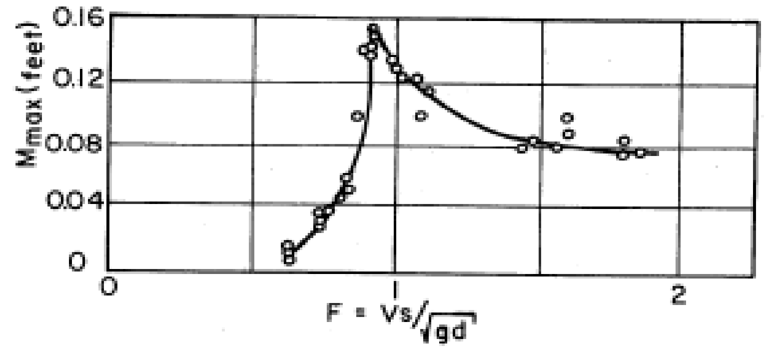



FIG. 7 MAX. WAVE HEIGHT AS A FUNCTION OF FROUDE NUMBER FOR A TYPICAL SHIP MODEL (JOHNSON, 1958)

$$F_L = \frac{V}{\sqrt{gL_s}} \qquad \text{where} \quad L_S = \text{ship length}$$

*or*

$$F_d = \frac{V}{\sqrt{gd}} \qquad \text{where} \quad d = \text{water depth}$$

# Empirical Model

## Variation of *H* with Distance from Sailing Line

- **Havelock (1908) theory for deep water:**
  - $H \sim y^{-1/3}$ for diverging waves
  - $H \sim y^{-1/2}$ for transverse waves
- **Empirical evidence in literature shows**
  - $H \sim y^{-0.25}$ to $H \sim y^{-0.6}$
- **Present study:**
  - Least-squares fit of both −1/3 and −1/2 models to data
  - Best-fit obtained with −1/3 power as

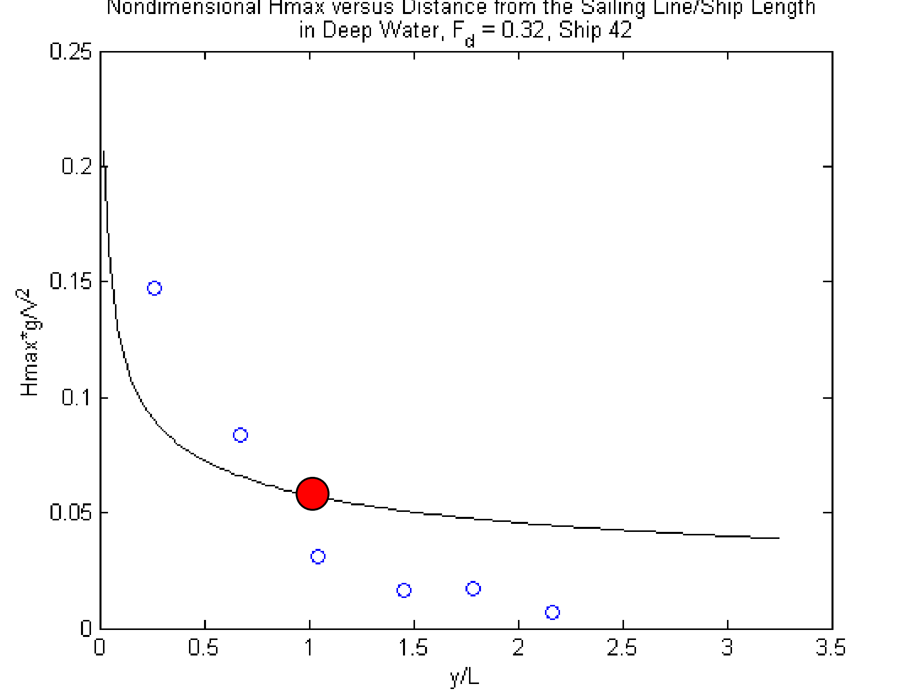
$$\frac{gH}{V^2} = C\left(\frac{y}{L}\right)^{-1/3}$$

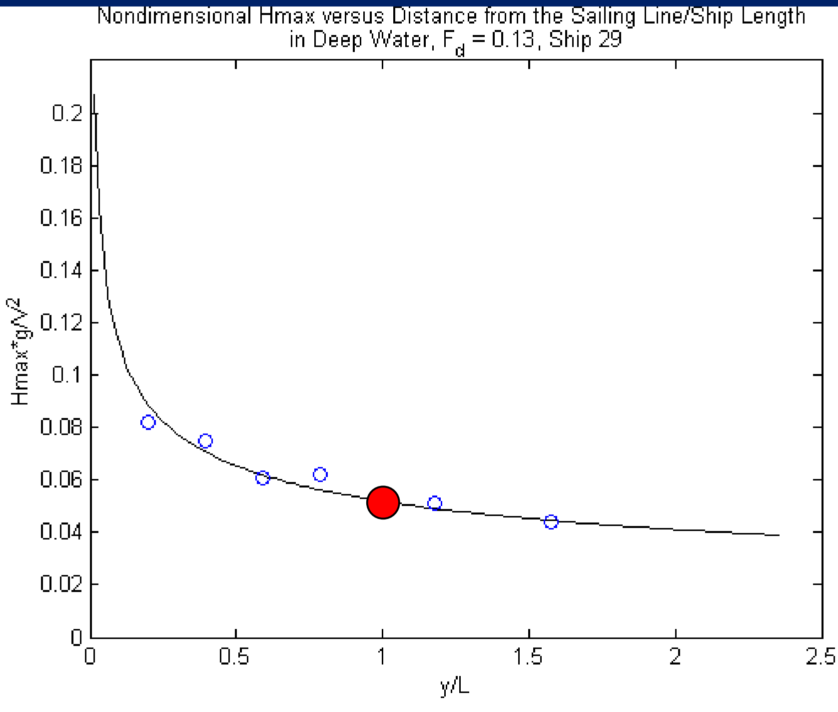
C varies with ship hull form, T/d, $F_d$ or $F_L$

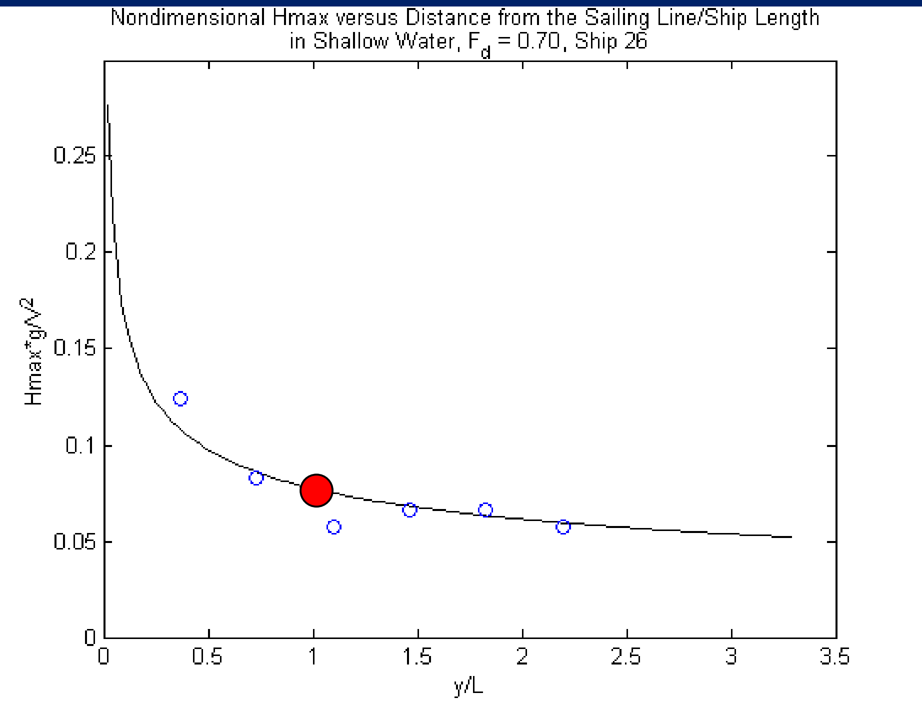
# Examples of Fit

$gH/V^2$ versus $(y/L)^{-1/3}$

**Value of $gH/V^2$ at y/L=1 used as a characteristic value for further analysis**

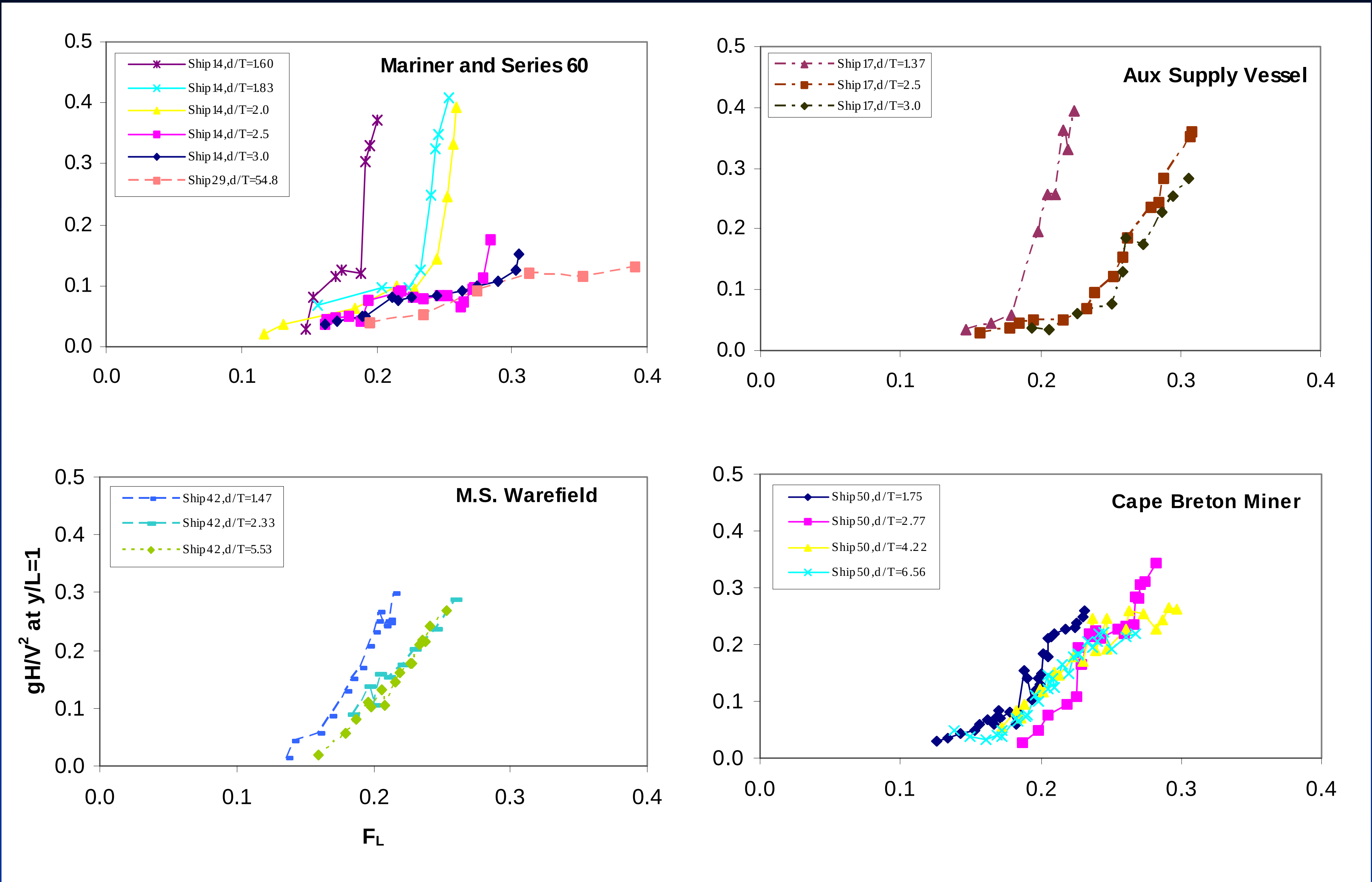


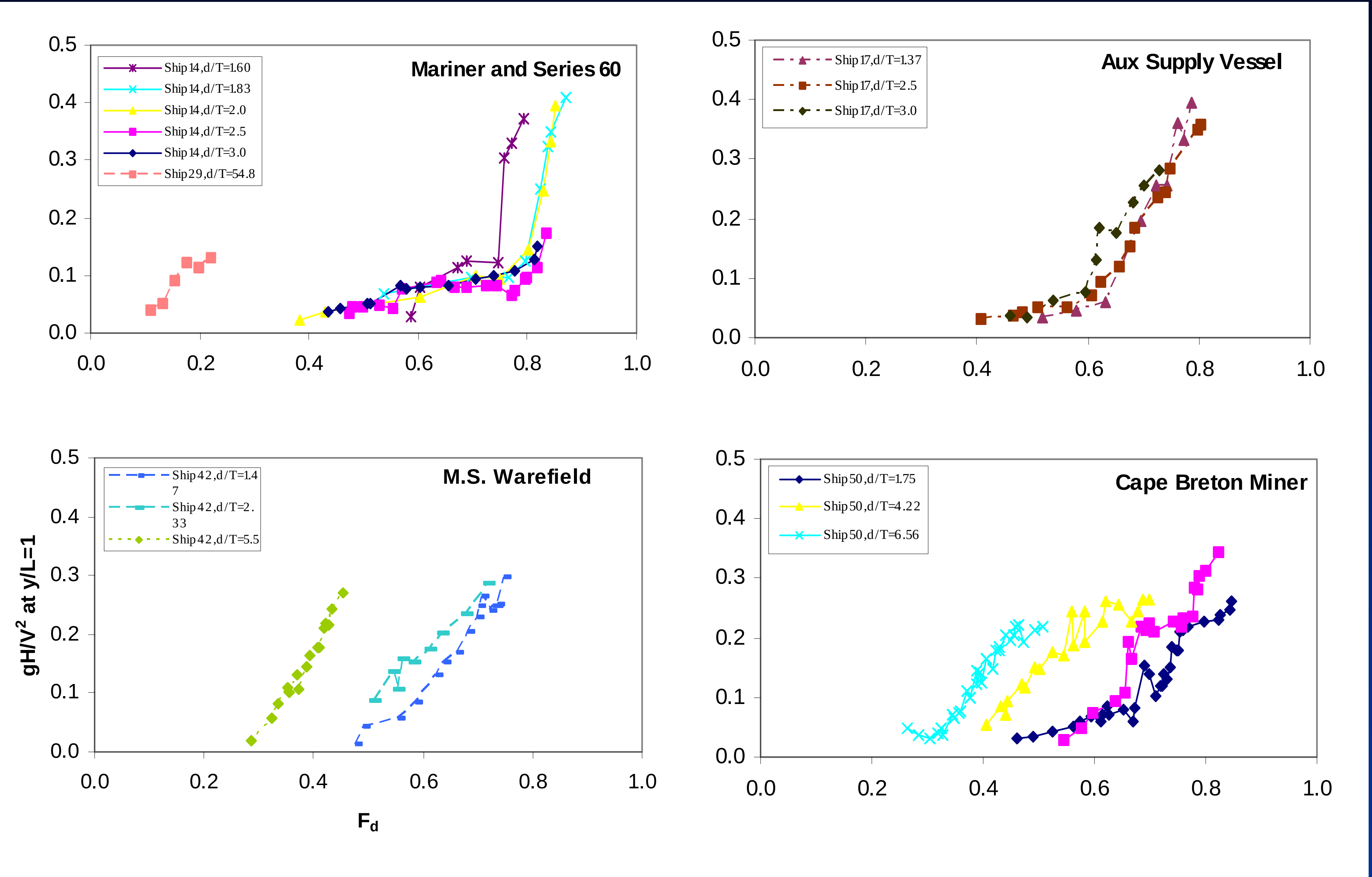
# gH/V² (at y/L=1)

## Plotted vs Length Froude Number $F_L$



# $gH/V^2$ (at y/L=1)

## Plotted vs Depth Froude Number $F_d$



# Is there some "Modified Froude Number" which will Unify Data?

$F_L$ works in deep water, not shallow

$F_d$ works in shallow water, not in deep

Is there a combination that works across all water depths?

Can we "collapse" data for a given ship to a single curve?

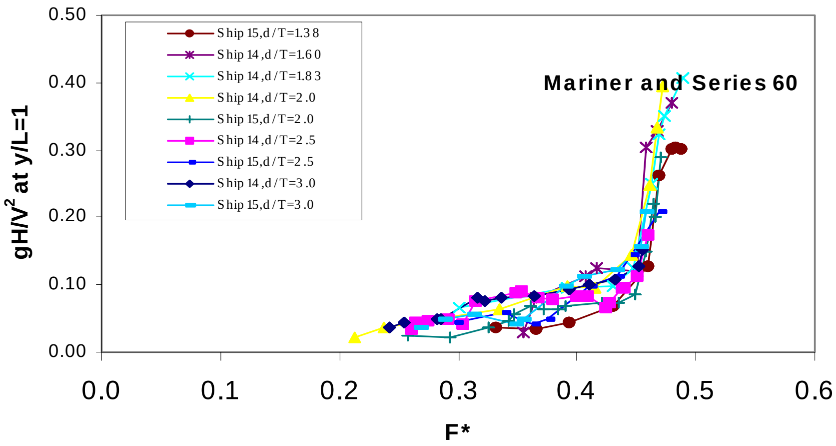
# Modified Froude Number, F*

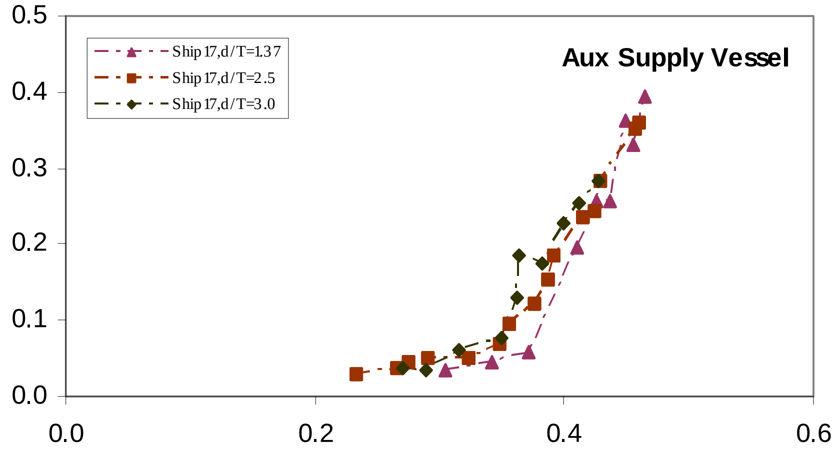
**After much trial and error…**

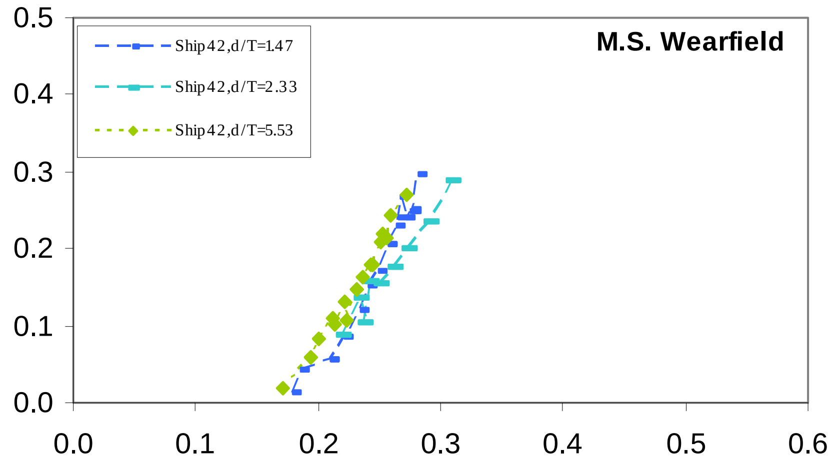
**Results for each ship collapsed to single curve when plotted against:**

$$F_* = F_L \exp\left(\alpha \frac{T}{d}\right)$$

**Single empirical coefficient $\alpha$ is dependent on hull form**



# Variation of $\alpha$ with Hull Form

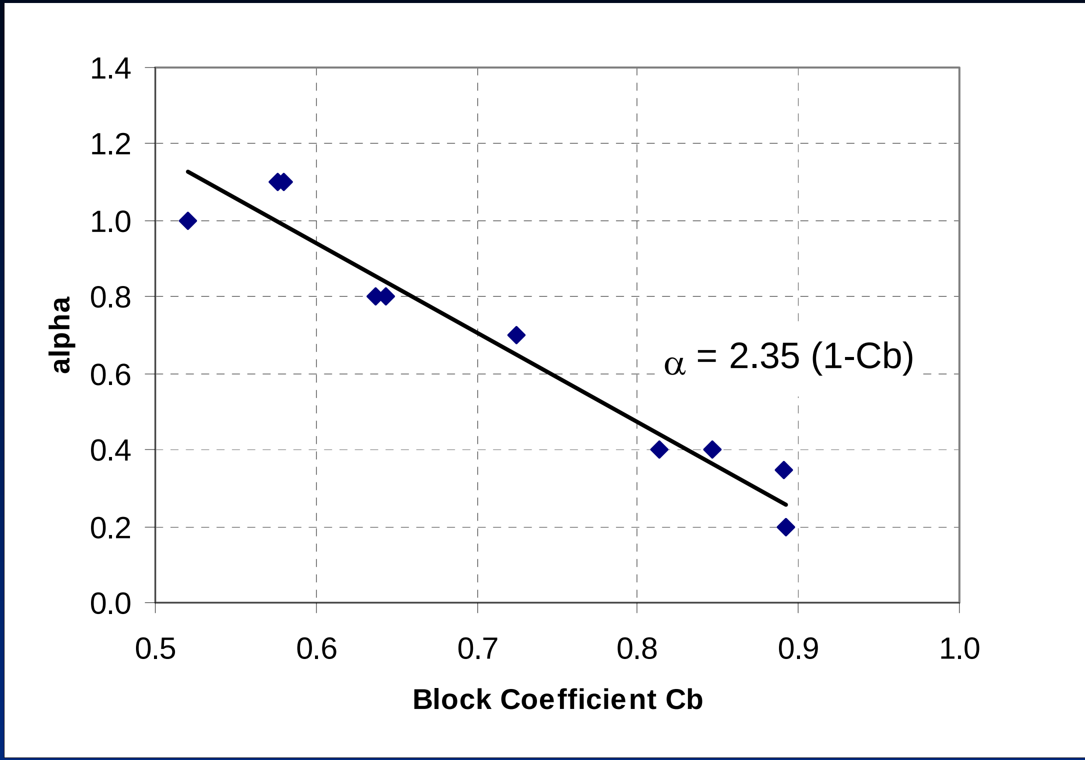
- **Investigated dependence of $\alpha$ on hull form**
- **Seems to depend mainly on Block Coefficient**

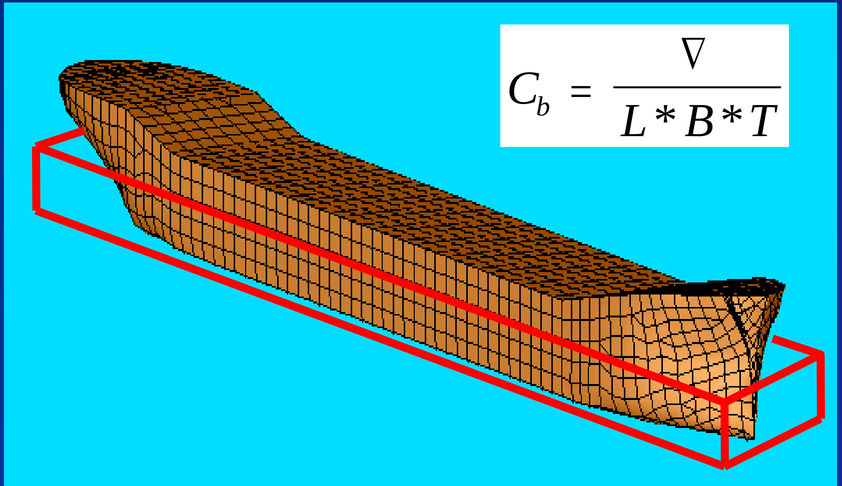
$$F_* = F_L \exp\left(\alpha \frac{T}{d}\right)$$

with

$$\alpha = 2.35\left(1 - C_b\right)$$

- **General trends:**
  - Streamlined hulls have $\alpha$ of 1 or more
  - Blunt hulls have $\alpha$ of 0.2 to 0.4



$$C_b = \frac{\nabla}{L * B * T}$$

# Now…Search for Relationship between $gH/V^2$ and $F_*$

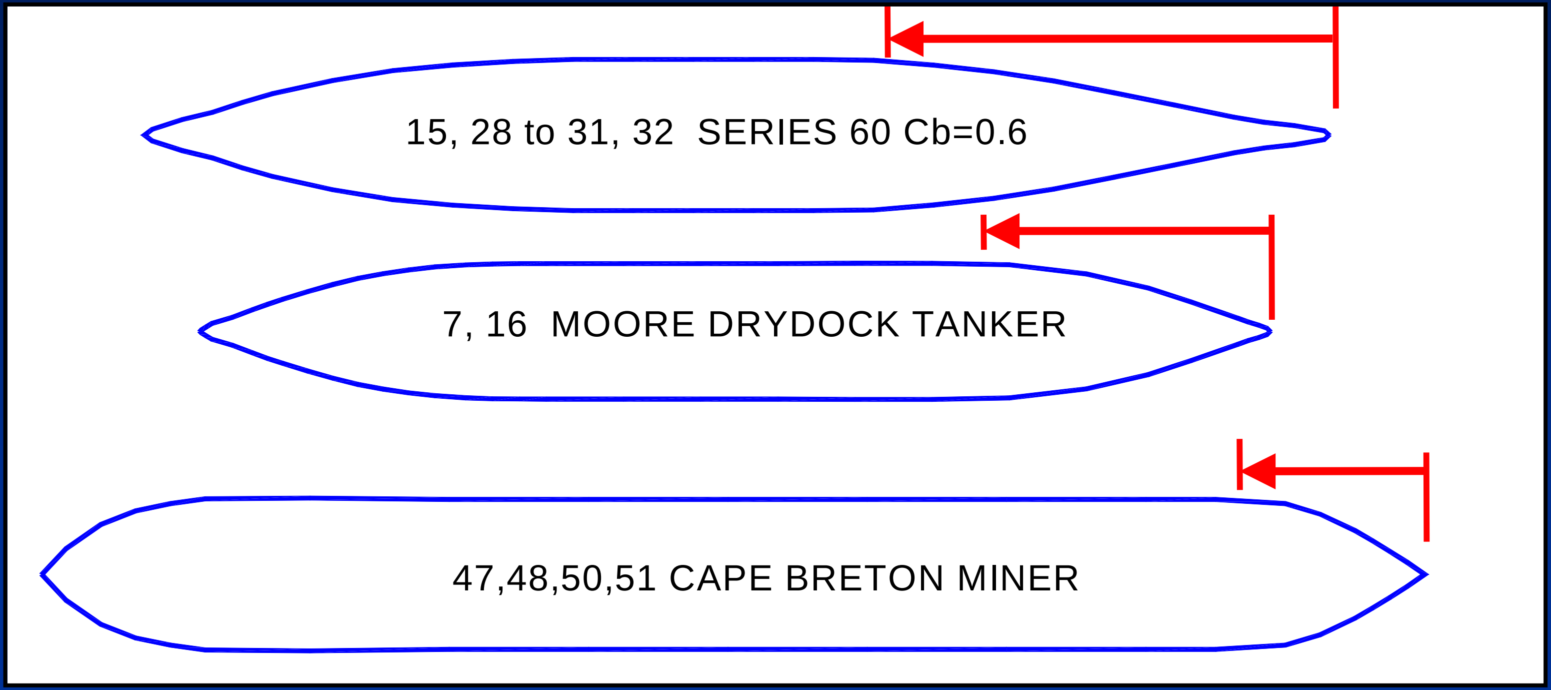
- Data for a given ship shows $gH/V^2$ increases with $F_*$
  - No waves measured for $F_*$ below 0.1
  - Data shows quadratic or higher order relationship
- No simple mathematical function seems to ideally describe all data for all hulls
- Adopted quadratic expression for simplicity

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2$$

$\beta$ varies with hull form

# Coefficient β seems to vary with Entrance Length, Le

- **Defined as length from bow to start of parallel middle-body**
- **Importance for ship waves noted by Saunders (1957)**
- **Used in other predictive models (Gates and Herbich, 1975)**



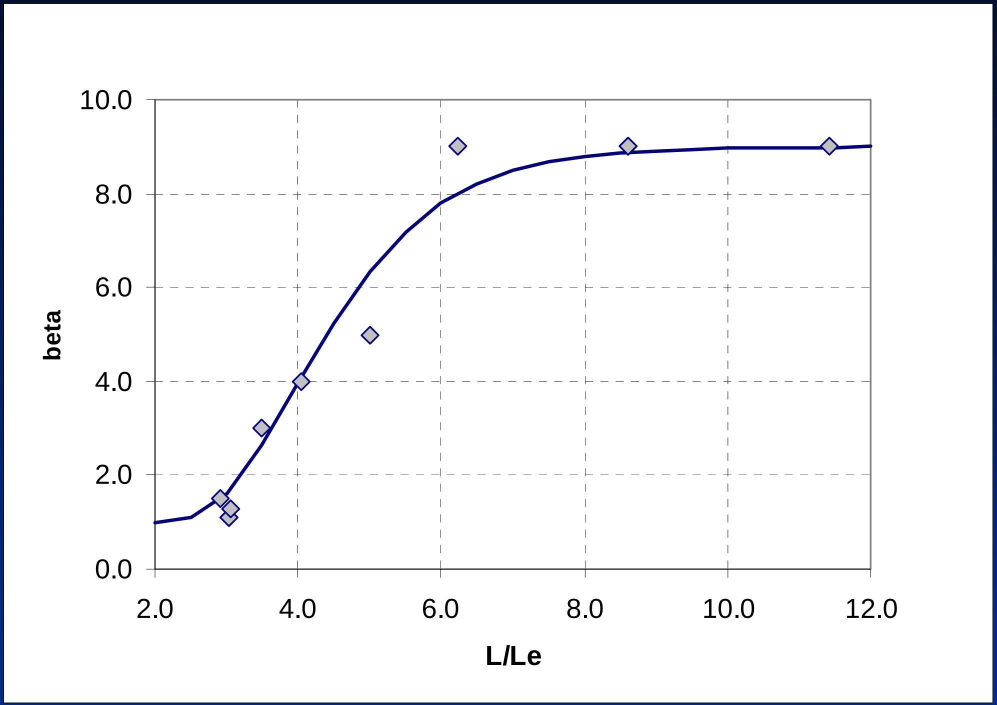
# Variation of β with Hull Form

β correlated to entrance length

- Best correlation was based on L/Le ratio
  - Streamlined ships have β of 1 to 2
  - Blunt hulls have β up to 9

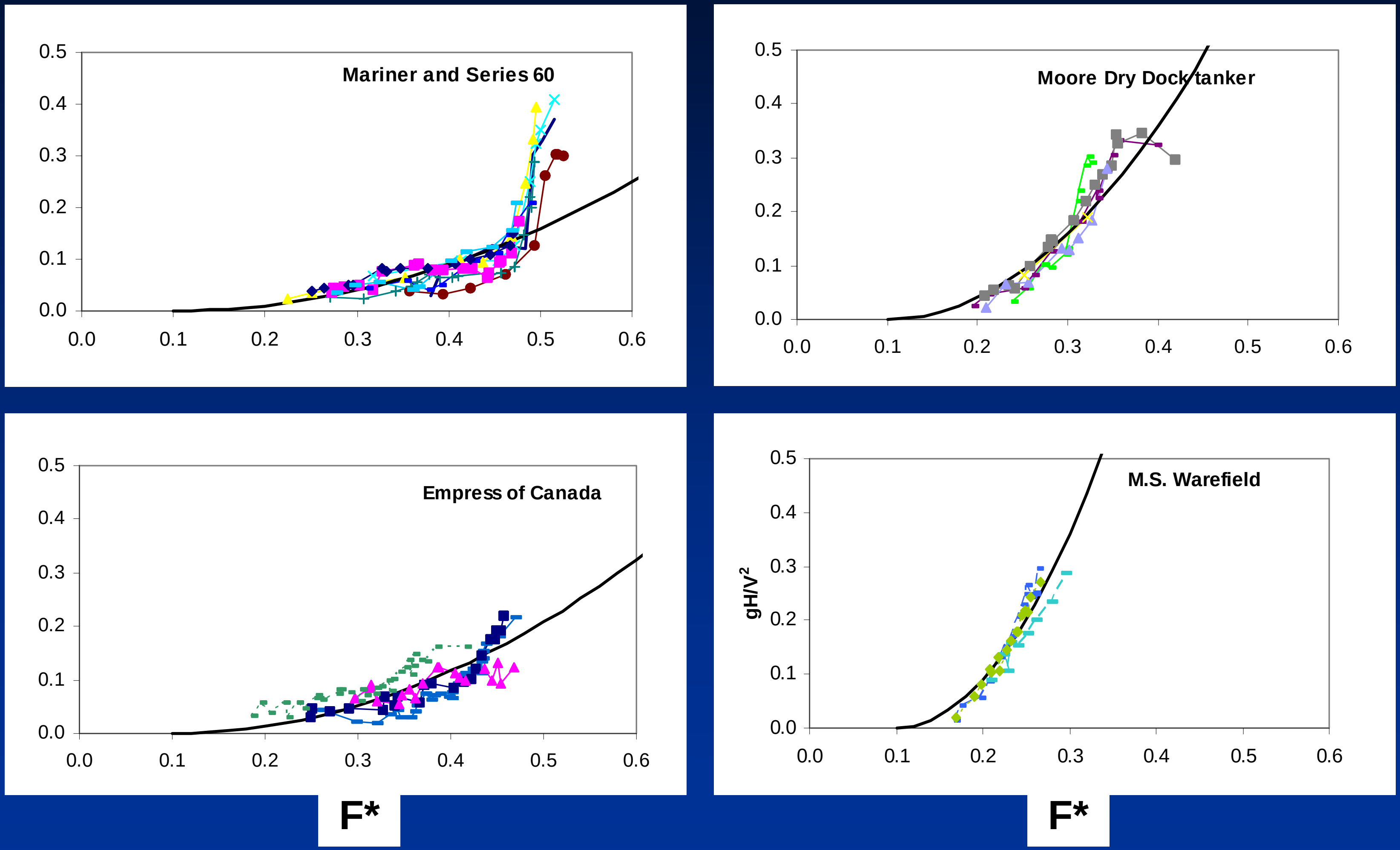
- Tentative relationship:

$$\beta = 1 + 8 * \tanh^{3}\left(0.45\left(\frac{L}{L_e} - 2\right)\right)$$



# Results for $gH/V^2$ (at y/L=1)
## Measured and Predicted

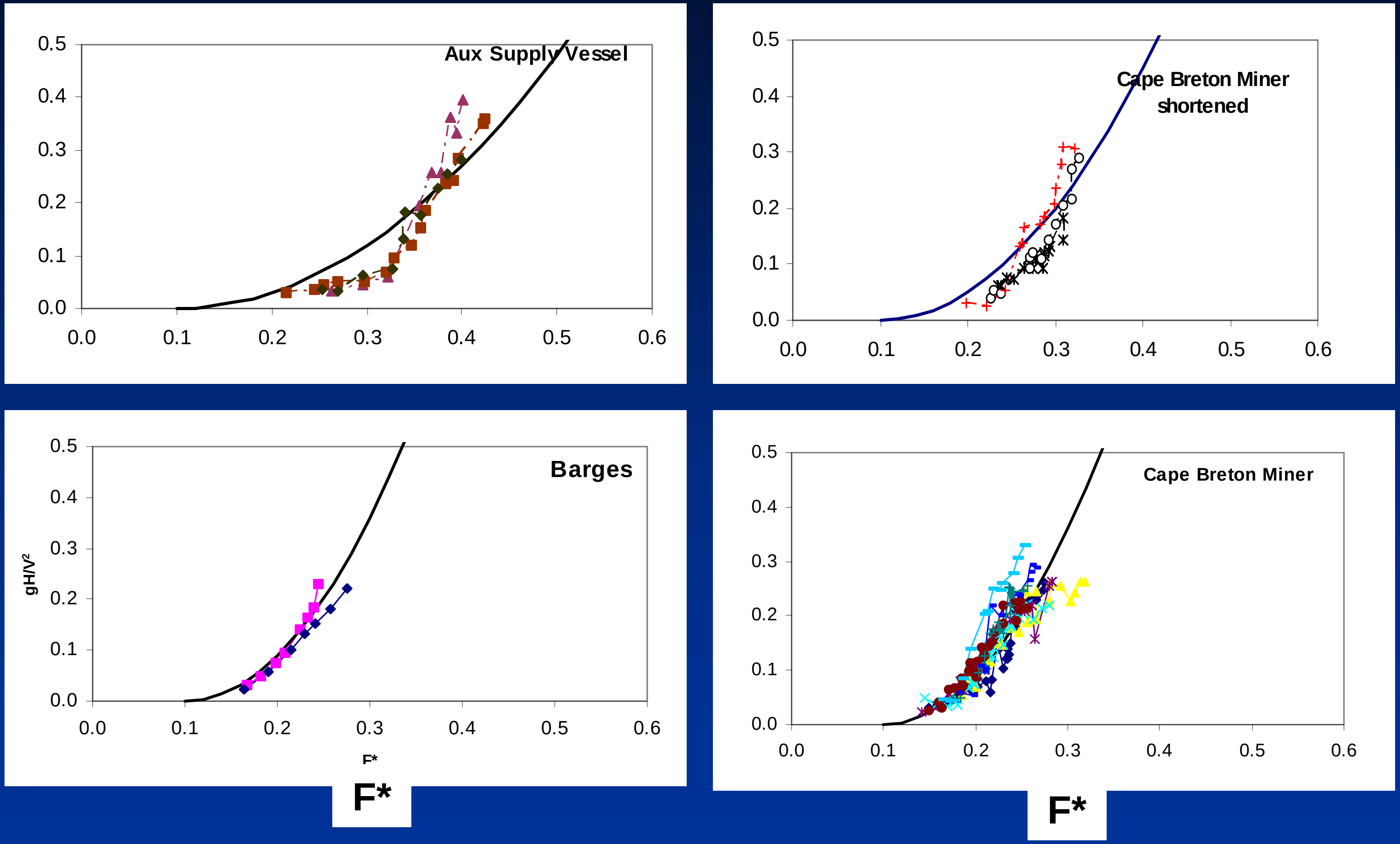
$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2$$



# Results for gH/V² (at y/L=1)

## Measured and Predicted

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2$$



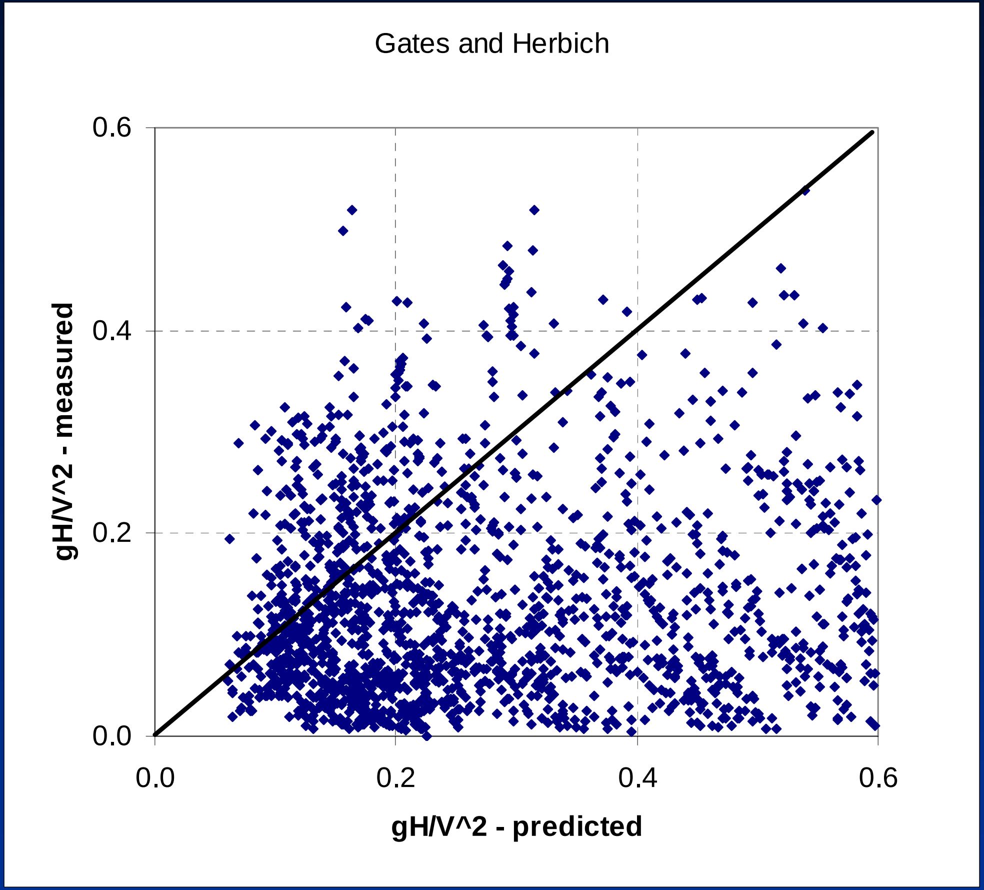
# Evaluation of Wave Height Models

## Gates & Herbich (1975)

– **Can be re-written in the f**

$$\frac{gH}{V^2} = k_w \frac{B}{L_e} F_L^{2/3} \left(\frac{y}{L}\right)^{-1/3}$$

– **Critical problems:**
- **Not dependent on depth-to-draft ratio (d/T)**
- **Data shows exponent on $F_L$ should be >1**



# Evaluation of Wave Height Models

- Sorensen & Weggel (1984) and Weggel & Sorensen (1986)

$$H^* = \alpha\left(Y^*\right)^n$$

where

$$\log \alpha = a + b \log d^* + c(\log d^*)^2$$

with

$$a = -0.6\,F_d^{-1} \quad b = 0.75\,F_d^{-0.125} \quad c = 2.653 F_d - 1.95$$

and

$$n = \beta\left(d^*\right)^\delta$$

with

$$\beta = -0.225\ \mathrm{F_d^{-0.699}} \quad \text{for} \quad 0.2 < F_d < 0.55$$

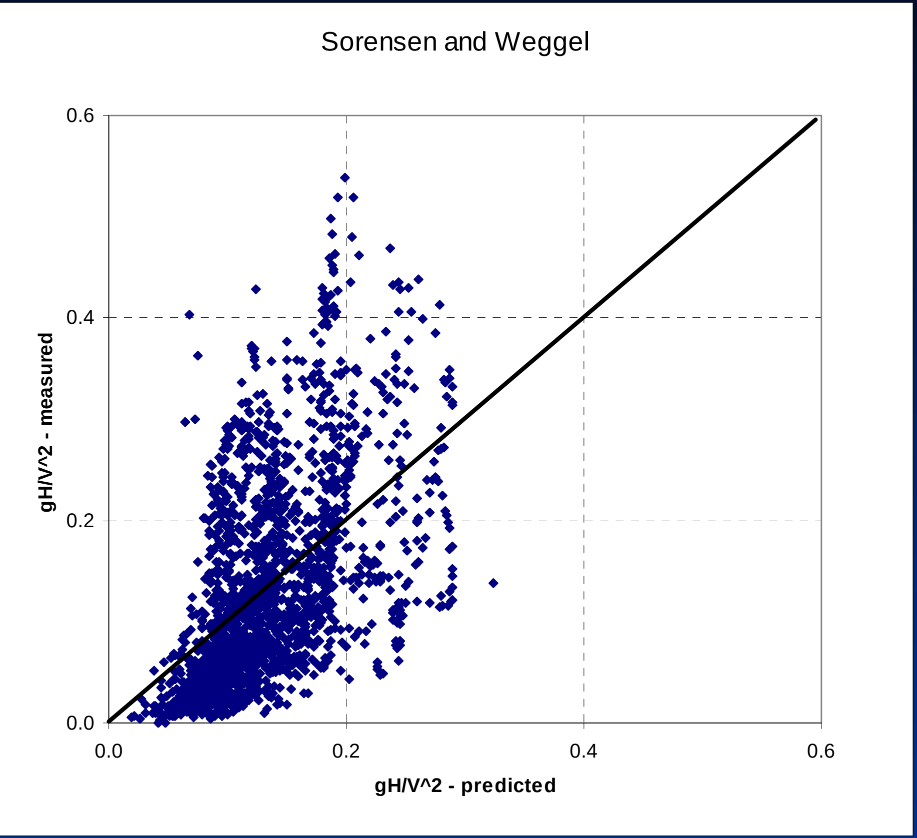
$$= -0.342 \quad \text{for} \quad 0.5 < F_d < 0.80$$

$$\delta = -0.118\ \mathrm{F_d^{-0.356}} \quad \text{for} \quad 0.2 < F_d < 0.55$$

$$= -0.146 \quad \text{for} \quad 0.5 < F_d < 0.80$$

*and*

$$H^* = \frac{H}{\nabla^{0.33}} \quad Y^* = \frac{Y}{\nabla^{0.33}} \quad d^* = \frac{d}{\nabla^{0.33}}$$



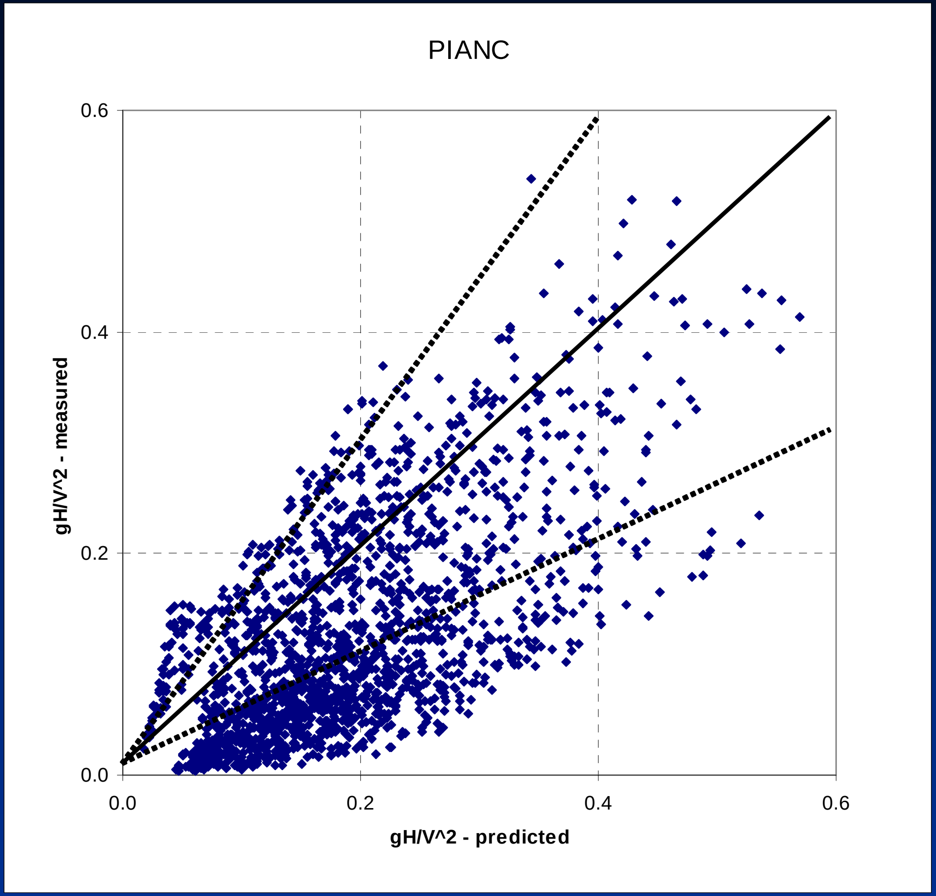

- A little complicated and removed from the physics
- Not dependent on hull form

# Evaluation of Wave Height Models

- **PIANC (1987)**
  - Based on work at Delft by Blaauw et al (1984) and others for ships in canals

$$\frac{gH}{V^2} = F_d^2\left(\frac{y - B/2}{d}\right)^{-1/3}$$

  - Similar functional form to proposed model but with $F_d$
  - Tends to over-predict



# Evaluation of Wave Height Models

## Proposed Model

**Gives best agreement of the models evaluated based on 1200+ data points**

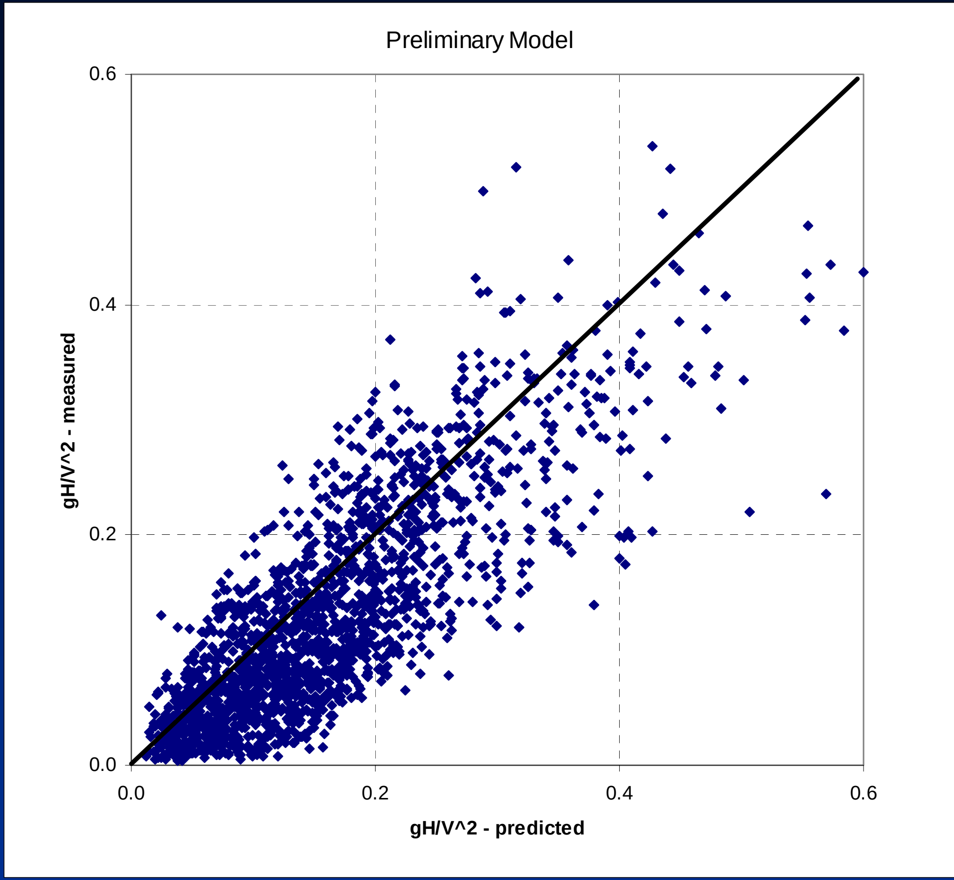
$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2 \left(\frac{y}{L}\right)^{-1/3}$$

where

$$F_* = F_L \exp\left(\alpha \frac{T}{d}\right)$$

$$\alpha = 2.5(1 - C_b)$$

$$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{Le} - 2\right)\right)$$



# Summary and Conclusions
# Ship-Generated waves

- **New model gives improved predictions**
  - $\exp(\alpha T/d)$ term “unifies” data
- **Model can be further improved**
  - **$(y/L)^{-1/3}$ can be optimized**
  - **$(F_*-0.1)^2$ can be optimized**
- **Need more data in shallow water**
  - **Lab data for very shallow water $T/d < 1.3$**
  - **Field data**
- **Try F* approach on Fast Ferries**

$$\frac{gH}{V^2} = \beta\left(F_* - 0.1\right)^2 \left(\frac{y}{L}\right)^{-1/3}$$

where

$$F_* = F_L \exp\left(\alpha \frac{T}{d}\right)$$

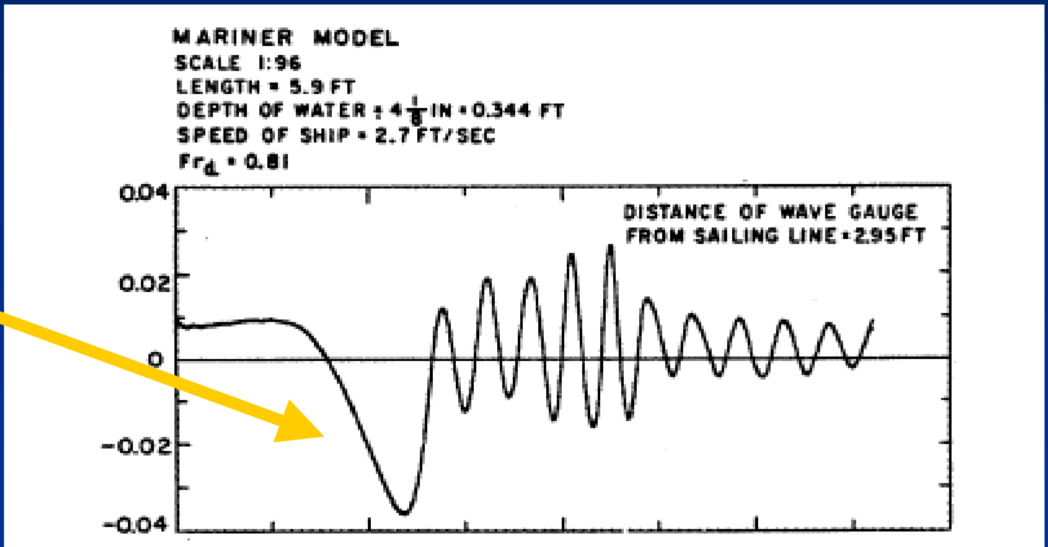
$$\alpha = 2.35(1 - C_b)$$

$$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{Le} - 2\right)\right)$$

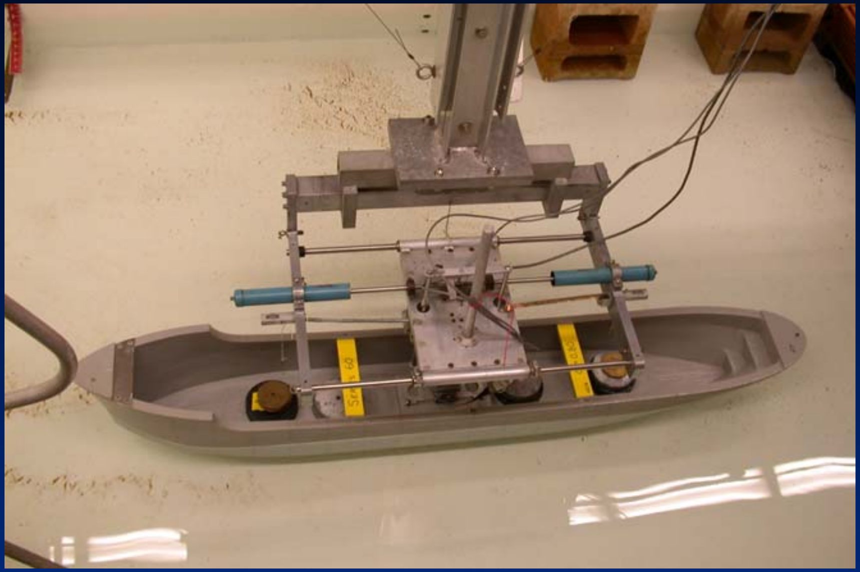
# Other Recent Work on Vessel Effects

- **Physical Model Study of Vessel Squat in Shallow Water:**
  - Lab tests in Naval Academy towing tank
  - Measured drawdown and ship-generated waves
  - Measured ship squat and trim
  - Developed empirical equations based on F* concept

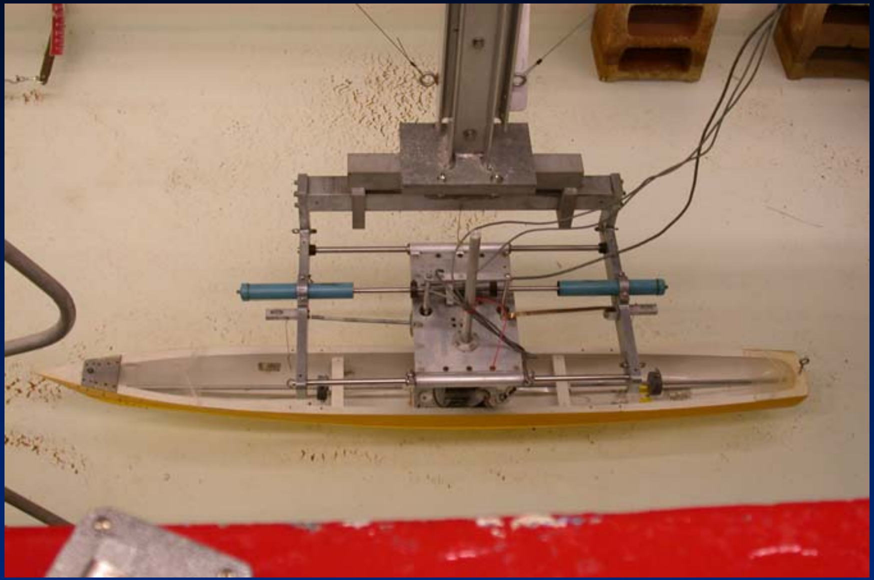
Drawdown is local depression of water surface near hull in shallow water



# Test Conditions

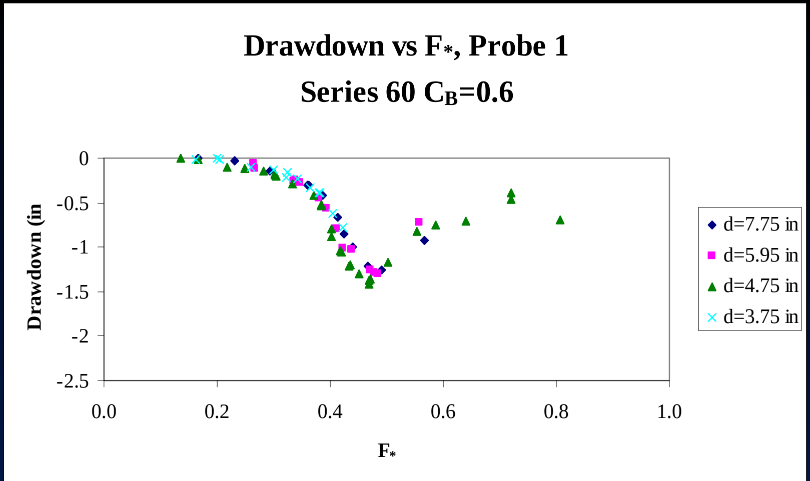


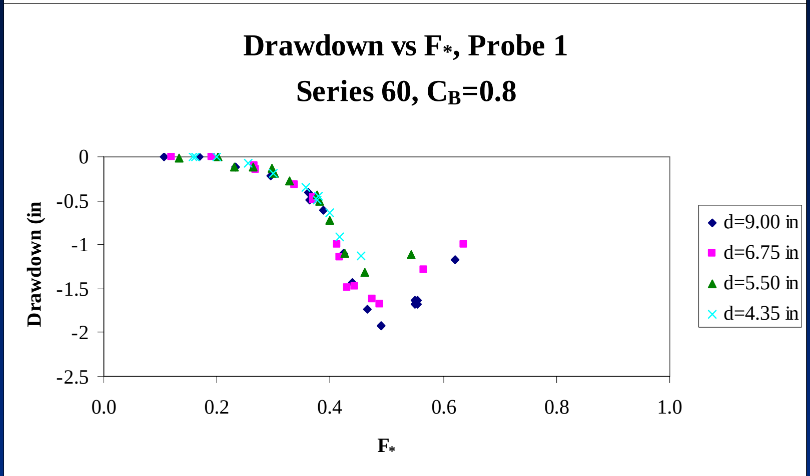
Series 60 Generic Commercial Hull
$C_B = 0.80$ and $C_B = 0.60$

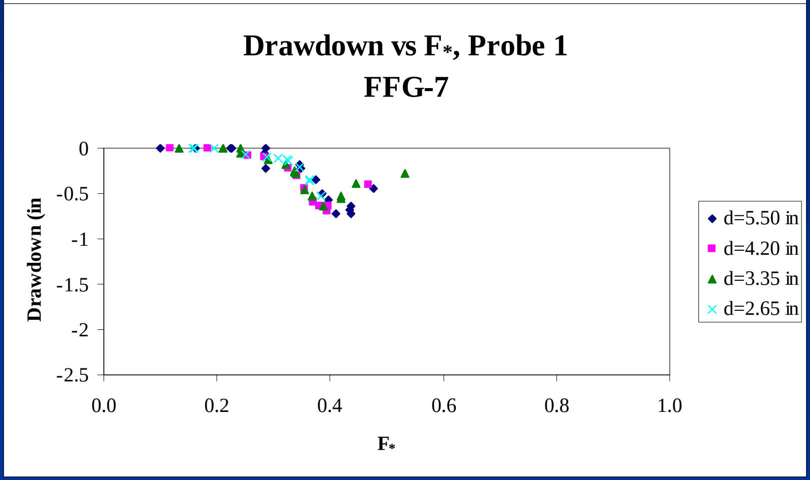


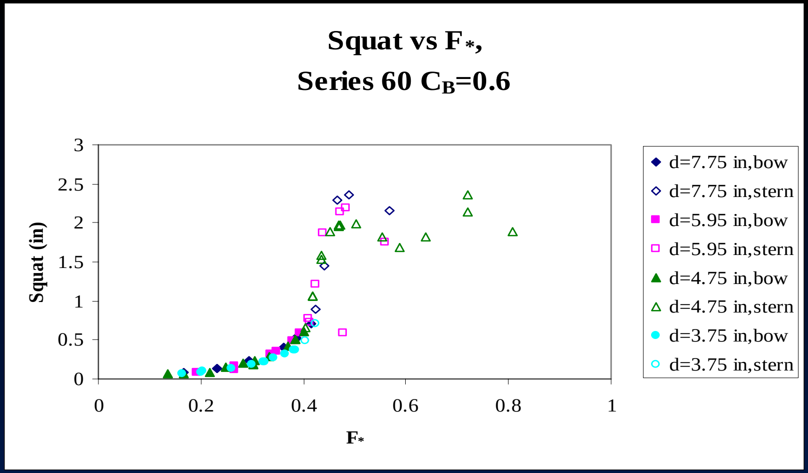
FFG-7 Class Frigate
$C_B = 0.44$

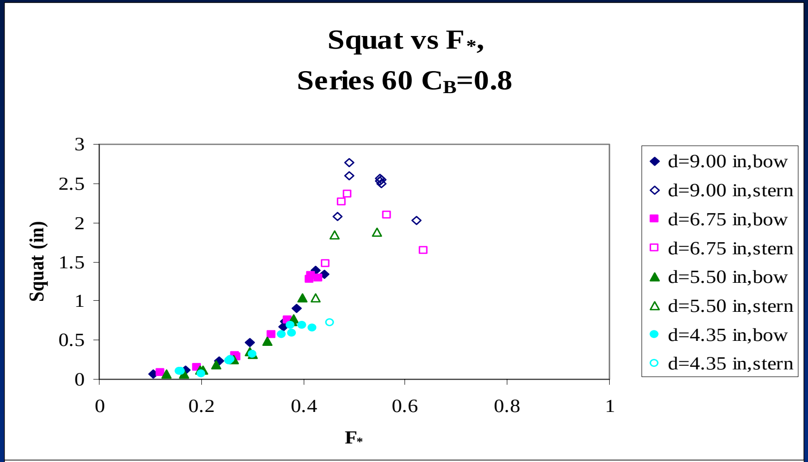
Shallow water with d/T from 1.15 to 3

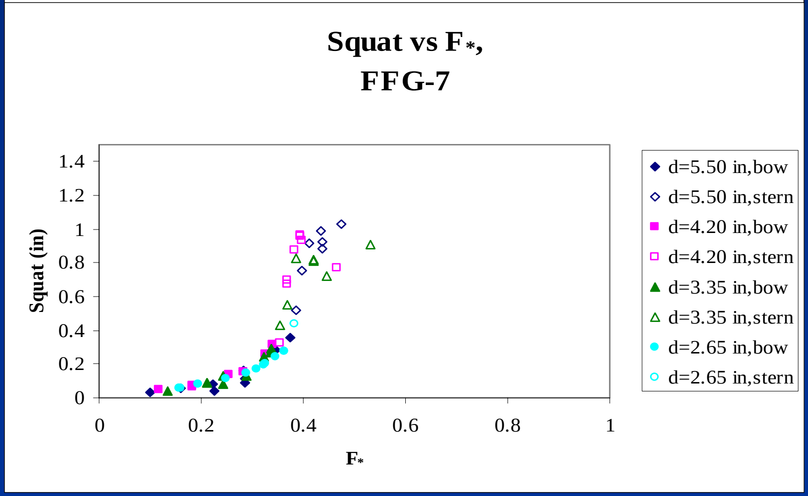

Drawdown vs F*, Probe 1
Series 60 $C_B$=0.6
Drawdown (in
F*
0
-0.5
-1
-1.5
-2
-2.5
0.0
0.2
0.4
0.6
0.8
1.0
d=7.75 in
d=5.95 in
d=4.75 in
d=3.75 in

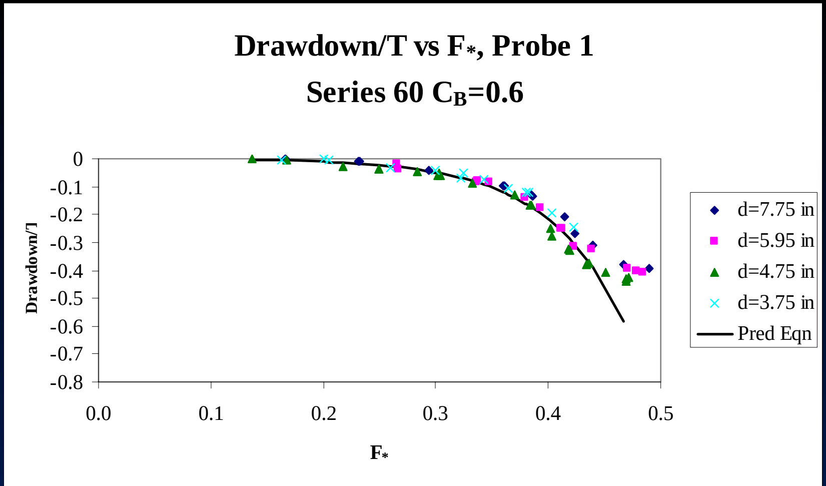

Drawdown vs F*, Probe 1
Series 60, $C_B$=0.8
Drawdown (in
F*
0
-0.5
-1
-1.5
-2
-2.5
0.0
0.2
0.4
0.6
0.8
1.0
d=9.00 in
d=6.75 in
d=5.50 in
d=4.35 in

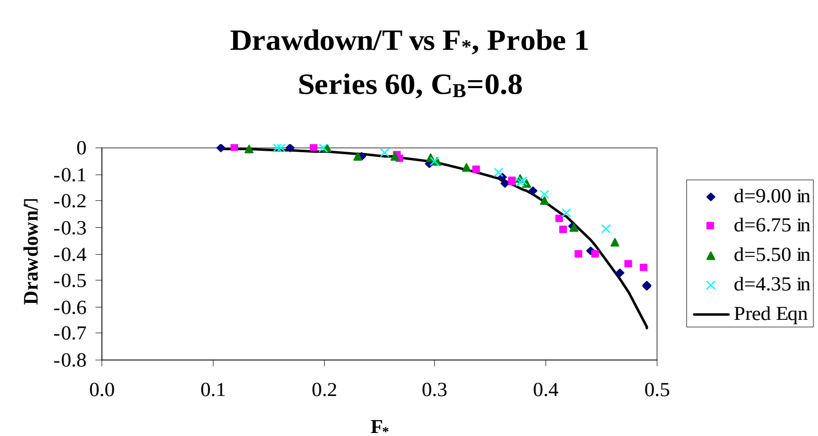

Drawdown vs F*, Probe 1
FFG-7
Drawdown (in
F*
0
-0.5
-1
-1.5
-2
-2.5
0.0
0.2
0.4
0.6
0.8
1.0
d=5.50 in
d=4.20 in
d=3.35 in
d=2.65 in

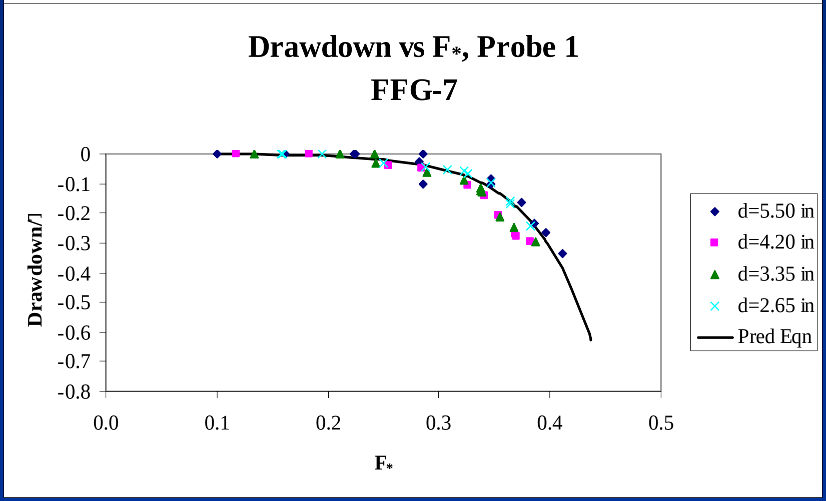

Squat vs F*,
Series 60 $C_B$=0.6
Squat (in)
F*
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
d=7.75 in,bow
d=7.75 in,stern
d=5.95 in,bow
d=5.95 in,stern
d=4.75 in,bow
d=4.75 in,stern
d=3.75 in,bow
d=3.75 in,stern


Squat vs F*,
Series 60 $C_B$=0.8
Squat (in)
F*
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
d=9.00 in,bow
d=9.00 in,stern
d=6.75 in,bow
d=6.75 in,stern
d=5.50 in,bow
d=5.50 in,stern
d=4.35 in,bow
d=4.35 in,stern


Squat vs F*,
FFG-7
Squat (in)
F*
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
d=5.50 in,bow
d=5.50 in,stern
d=4.20 in,bow
d=4.20 in,stern
d=3.35 in,bow
d=3.35 in,stern
d=2.65 in,bow
d=2.65 in,stern



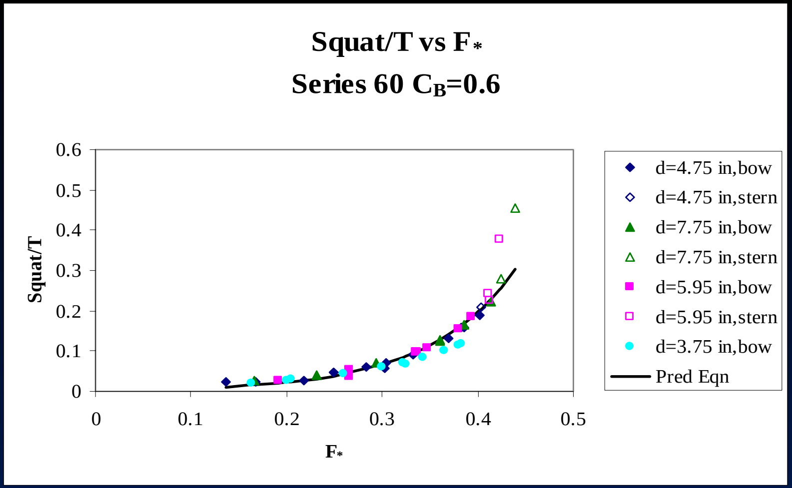

# Drawdown

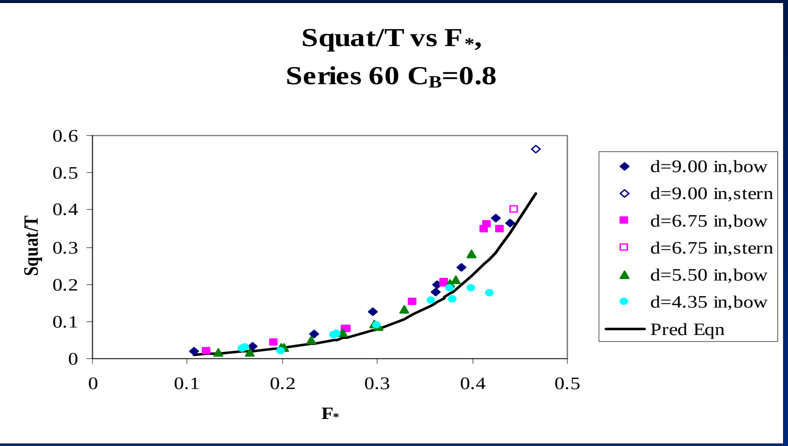
## Subcritical Conditions

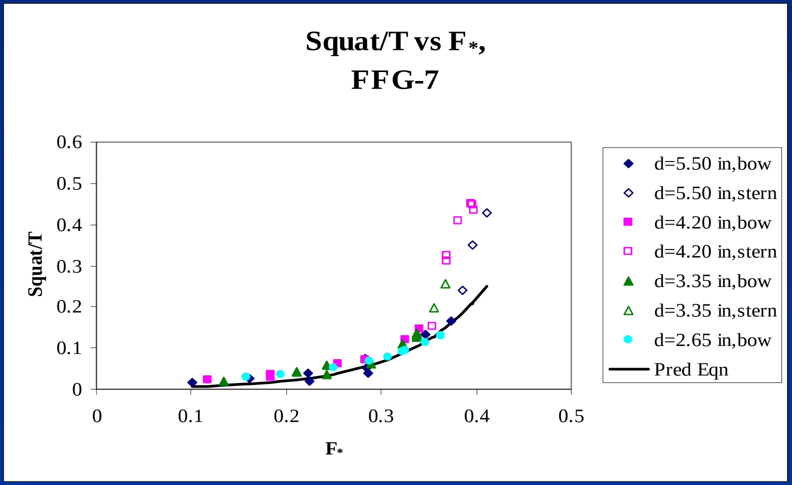
$$\frac{Drawdown}{T} = C_1 \exp(C_2 F_*)$$

$$C_1 = 0.0026 C_B - 0.001$$

$$C_2 = -215.8 \frac{T}{L} + 26.4$$




# Ship Squat

## Subcritical Conditions

$$\frac{S}{T} = C_3 \exp(C_4 F_*)$$

$$C_3 = 0.005 C_B - 0.0004$$

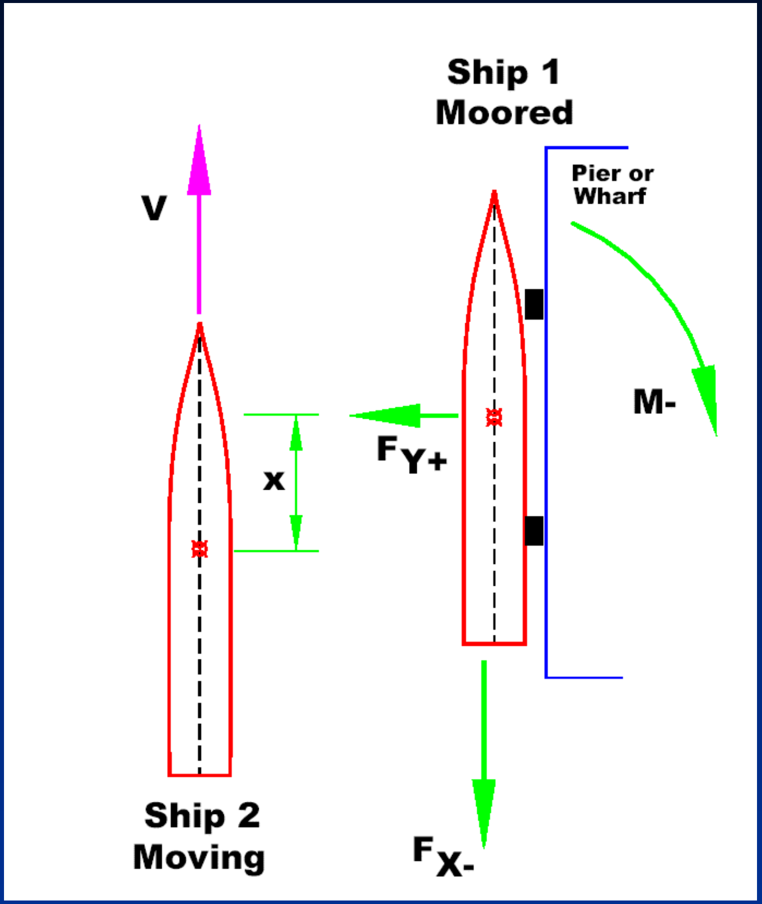
$$C_4 = -61.46 \frac{T}{L} + 14.10$$

**Results compared favorably to other formulas for predicting ship squat:**

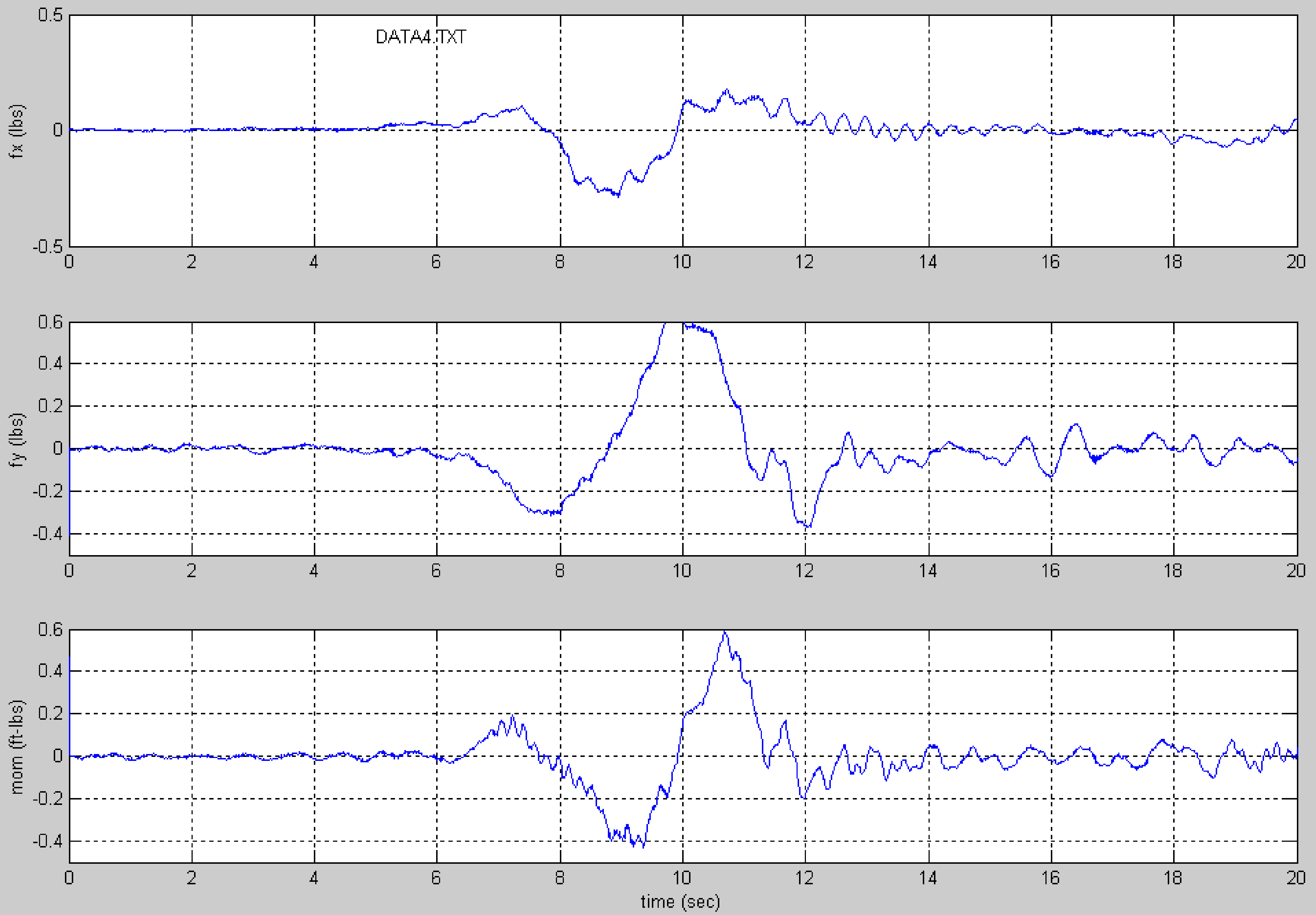
ICORELS, Huuska/Guliev, and Millward

# Other Recent Work on Vessel Effects

- **Mooring Loads from Passing Vessels:**
  - Lab tests started at Naval Academy in August 2003
  - Measure loads on moored vessel caused by passing vessel
  - Develop database for NAVFAC to evaluate and validate numerical codes



# Passing Vessel Tests


DATA4.TXT
fx (lbs)
0.5
0
-0.5
fy (lbs)
0.6
0.4
0.2
0
-0.2
-0.4
mom (ft-lbs)
0.6
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
10
12
14
16
18
20
time (sec)